DAKOTAS WIND TRANSMISSION STUDY

TASK 2

Transmission Technologies to Increase Power Transfers

FINAL REPORT

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Technical Report

Dakotas Wind Transmission Study	**No. 2005-10977-3 R2**		
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Summary:

This report documents the status of results for Task 2 of the Dakotas Wind Transmission Study. Task 2 provides an overview of some of the transmission technologies to mitigate overloads and stability problems without adding new transmission lines to the system. The results of the Task 3 and 4 studies indicated some steady-state and dynamic stability problems when wind generation was added. For two of the sites there were some possible transmission line overloads following a contingency. Overloads at these two sites could potentially be resolved by using dynamic rating of the lines.

Under some system export conditions there were some system instability and low dynamic voltage problems. Simulations of series capacitor compensation and SVCs demonstrated how these technologies could improve the system performance for these dynamic problems.

The report reviews various methodologies available to mitigate some of the system problems identified in the Task 3 and 4 studies. The technologies considered in these study includes the following:

- Re-conductor transmission lines
- Dynamic transmission line ratings
- Add conventional series capacitors
- Add controllable series capacitors
- Add SVCs or STATCOMs
- Add phase shifting transformers

For the steady-state overloading problems, the dynamic transmission line rating and reconductoring the transmission lines can mitigate the problems. For the dynamic instability and low voltage problems, series capacitors and SVCs or STATCOMs can improve the system performance.

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Rev. #	Revision	Date	Author	Reviewed	Approved
2	Updated with Comments	10-19-05	RKV	DM	DM

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1 INTRODUCTION

There are several transmission alternatives besides building new transmission lines to accommodate more power transfers when new generation is connected to the power system. For steady state transmission improvements this study investigated the benefits of dynamic transmission line ratings, re-conductor of the transmission lines, phase shifting transformers for power control, and series capacitors for rerouting power flows. Dynamic rating of the transmission lines, also known as the real-time rating is the process of determining the design capacity of a transmission line and is calculated by making deterministic assumptions about the ambient temperature, wind speed and other weather related conditions. There are several ways of increasing the transmission capacity in real time. Re-conductoring a transmission line with larger conductor or a high temperature conductor can increase the transmission line capability. Some issues with re-conductoring are the cost effectiveness and the possible breaching of the statutory clearances with higher temperature conductors. Phase shifting transformers and series capacitors are methods to reroute power from lines that are overloaded to lines with spare capacity. They require some unused transmission capacity available on part of the system where they can reroute the power to use that capacity.

Stability limitations in the Dakotas also limit power transfers. Technologies that may increase the stability limits include series capacitors, both conventional or thyristor controlled, SVCs and STATCOMs, and phase shifting transformers.

2 DYNAMIC LINE RATING OF TRANSMISSION LINES

2.1 General Dynamic Rating Considerations

As a minimum up to a 15% or 20% increase in the thermal rating of a transmission can be obtained with dynamic ratings. Even more can be expected when the transmission lines are loaded due to wind generation since wind will be blowing when the lines are loaded. If an increase in the thermal rating of a transmission is needed, dynamic rating of the lines may be an option. In the absence of a dynamic rating capability, transmission owners are restricted to operating the lines at a pre-determined limit computed with a fixed set of weather conditions including ambient temperature, sunshine, wind velocity and direction, etc which affect the current carrying capability of the transmission line. The steady state thermal rating is the loading that corresponds to the maximum allowable conductor temperature under the assumption of thermal equilibrium. The dynamic security rating of the line is a function of the line admittance. Figure 1. shows the relationship between the line length, thermal ratings and security or stability constraints. The curved labeled dynamic line rating refers to the dynamic stability rating and not the dynamic thermal rating. A line that has dynamic thermal rating capability will results in the thermal line rating curve being raised higher based on weather and ambient conditions.

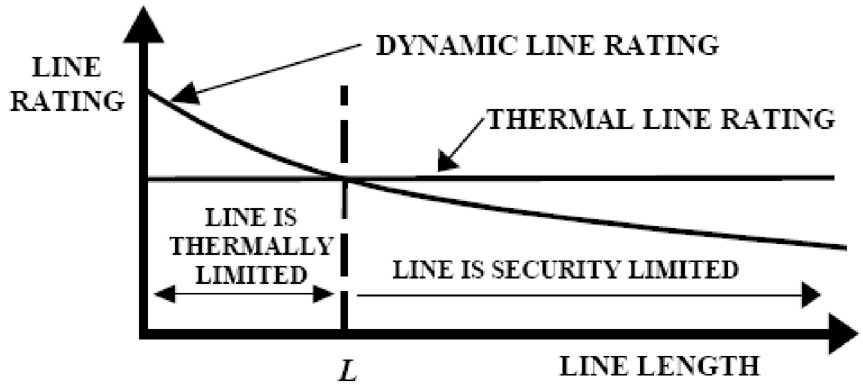

Figure 2.1 Line Rating (vs) Line Length

Interconnection of the wind generation is interesting in its correlation to the weather factors that affect the dynamic line ratings. Wind generators output increases with wind velocities. Normally as the wind increases, the generation increases and results in higher loadings on the transmission lines. The interconnecting transmission lines have a nominal rating calculated at much lower wind speeds. At higher wind velocities, the cooling of the transmission line reduces the sag there by making the transmission line available for more power transfers at the time the wind generation is adding to the power transfers.

Dynamic rating of the line allows the transmission owner to monitor the weather conditions, sag / tension on the line in real time and to permit loadings that exceed the nominal rating. All lines in Unites States are governed by the National Electric Safety code (NESC). The most common practice is to calculate line nominal ratings based on coincident high ambient temperature, full solar radiation and effective wind speed of 0.61 m/s. Some utilities even assume an effective wind speed of 0.91 m/s, or higher.

2.2 IEEE and CIGRE Standards

IEEE (IEEE standard 738, 1993) and CIGRE (CIGRE, 1992, 1997, 1999) offer standard methods for the calculation of the transmission line ampacity in the steady state and dynamic states. The CIGRE report presents a three-dimensional thermal model of conductors for unsteady state calculation. A similar model was presented to IEEE for the calculation of the thermal gradient of conductor from surface to the core.

Common utility practice of rating the transmission lines is based on the conservative assumptions of ambient temperature, wind speed, solar radiation and maximum conductor temperature:
Ambient temperature: 40 deg C
Wind speed: 0.61 m/s (2 ft/sec)
Solar Radiation: 1000 W/m^2
Maximum conductor temperature: 80 deg C

The solution of the differential equations for the heating of a conductor by current in the steady state and dynamic states requires the knowledge of the following metrological data as follows:

- Ambient Temperature
- Wind Speed
- Wind Direction
- Solar radiation

An example to consider is the wind generation interconnection, which takes into account the autocorrelations between the wind speed, wind direction, ambient temperature, solar radiation and other weather patterns to forecast the transmission line ampacity.

The approach to increase the thermal line ratings encompasses several active tasks:

- Develop thermal ratings standards,
- Identify sources and magnitudes of errors in as-built sags at every temperature,
- Accurate calculation of high temperature sags,
- Probabilistic aspects of the line ratings
- Real-time rating methodologies, etc

2.3 Static and Dynamic Ratings

The static ratings of the lines are determined based on the historical weather data in the region for different conductor types used in the region. Generally, static line ratings are fixed for a particular season of the year.

Dynamic line ratings are computed by online or offline methods based on recorded data. Methods to increase the maximum conductor temperature involve physical modifications for the line structures to increase ground clearance in certain spans. This method allows the use of higher allowable maximum conductor temperature and yields a corresponding increase in the calculated thermal rating. The uncertainties of the sag at higher temperature can be resolved by monitoring the sag and tension at higher current carrying conditions. Without actual measurements, the line may not adequately ensure proper minimum ground and under build clearance.

Online rating methods include monitoring conductor temperature, weather conditions or tension along the transmission line route. Installing temperature sensors at certain sections of the transmission line monitors conductor temperature. Tension monitors that are attached to insulators on the tension towers oversee conductor tension. In both monitoring systems, sensor data is communicated to a base station computer by a radio communication device installed on the sensor and the ampacity is calculated at the base station computer using the recorded data.

In the offline system, line ratings are obtained uniquely by monitoring weather conditions along the transmission line. The offline system may also include monitoring conductor sag by pointing a laser beam at the lowest point of the conductor in a span. The ampacity is calculated from the conductor sag and weather data by taking a series of measurements of conductor sag at a different transmission line spans along the length of the line.

Transmission lines are now being equipped with fiber optic network cables embedded in the core are used to carry useful information regarding the sag and temperature and eliminate the need for separate communication to supply data to the central processing station in order to determine the dynamic rating of the power lines. The latest advances in computation models involve probabilistic modeling of the conductor temperature to predict the loss of the tensile strength and permanent elongation of the conductor in the lifetime.

2.4 Heat Balance Equation For Calculating Allowable Conductor Loading

The following paragraphs describe briefly the mathematical formulation to evaluate the ampacity of a conductor.

Online temperature monitoring system:

There are many methods for calculation line loading. Most commonly used method uses the conductor temperature to solve the heat balance equation to evaluate the ampacity.

All the quantities are a function of the conductor temperature. Line ampacity is accurately computed by numerical solution of the following conductor temperature differential equation:

$$M.c_p.\frac{dT_{av}}{dt} = Pj + Ps + Pm - \Pr - Pc$$

M = γ.A, conductor mass, kg/m
A = conductor are, m^2
P_j = joule heating, W/m
P_S = solar heating, W/m
P_m = magnetic heating, W/m
P_r = radiation heat loss, W/m
P_C = convection heat loss, W/m
T_{av} = is the average of surface temperature and the core temperature of the conductor.

The ampacity is then calculated by using the formula:

$$I = \sqrt{(\Pr + Pc - Ps)/Rac}$$

Where;

P_r: Heat loss by radiation,
P_C: Heat loss by convection,
P_S: Heat gained by solar radiation,
R_{ac}: AC resistance of the conductor

Effect of wind speed and direction on the Ampacity of the conductor:

The wind speed at any instant effects the calculation of the dynamic rating of the line due to its effect on the Heat loss due to convection. It is given by the term P_C in the equation below.

$$\mathbf{P_C = h.\, \pi.\, D\, (T_c - T_a)}$$

h = coefficient of heat transfer from the conductor surface to the ambient air.

$$\mathbf{h = \lambda.\, Nu\, .\, K_{wd} / D}$$

λ = Thermal conductivity of ambient air
Nu = Nusselt number

$$\mathbf{Nu = 0.64\, Re^{0.2} + 0.2\, Re^{0.61}}$$

Re = Reynolds number

$$\mathbf{Re = D.\, (w_s/v_f)}$$

w_s = wind speed (m/sec)
v_f = kinematic viscocity of the air (m2/sec)
k_{wd} = wind direction correction factor

$$\mathbf{K_{wd} = 1.194 - \sin(\omega) - 0.194 \cos(2\omega) + 0.364 \sin(2\omega)}$$

ω = Wind direction with respect to conductor normal in degrees

Summary of methodology for calculating steady-state thermal rating (Offline Method) :

Receive Input From Steady – State Session Window → Heat Gain By Radiation, Ps → Radiation Heat Loss, Pr → Convection Heat Loss, Pc → $I = \sqrt{\dfrac{Ps - Pr - Pc}{Rac}}$

Example Calculation:

The Plot in figure 2.1 indicates the ampacity of the transmission line calculated based on the following assumptions:

Conductor Type: ACSR Cardinal conductor
Ambient temperature: 80 deg C
Solar Radiation: 1000 W/m^2
Emissivity = 0.5
Absorptivity = 0.5

Based on the above-mentioned values, the solar heat gain is computed to be 15.19 W/m and the Heat loss by radiation is calculated to be 22.08 W/m.

Using the formulation from the section 2, the Heat loss by convection is computed for various values of wind speed and direction.

The Figure 2.2 indicates the increase in the current rating of the line considered with the increase in the wind speed and variation in the direction of incidence of the wind on the conductor.

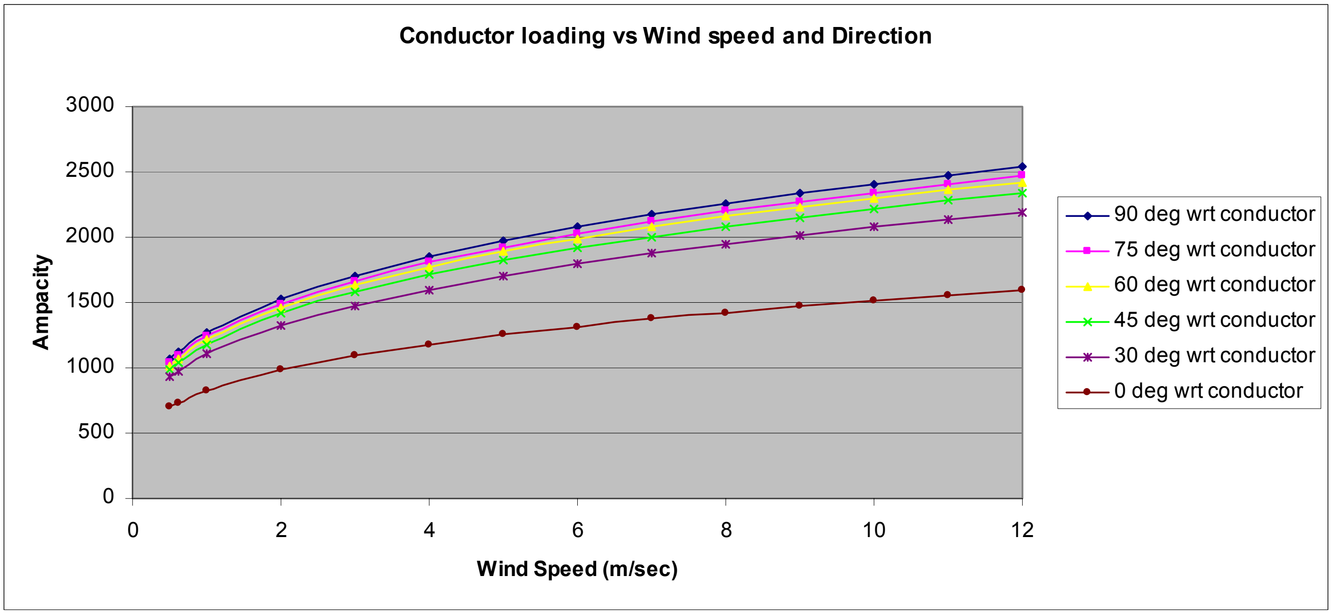

Figure 2.2 Line Rating (Vs.) Wind Speed And Angle Of Incidence

The above curves indicate the rating of the conductor based on the wind speed and the angle of incidence of the wind on the conductor. Clearly, the line can be rated at the maximum, for high wind velocities and also when the wind direction is perpendicular to the conductor.

The above curves are for an ACSR cardinal conductor with a mean diameter of 0.0304m. The conductor initial temperature is assumed to be 80 deg C.

Considering the wind velocities for the same angle of incidence (eg., 45 deg) the rating of the conductor can be increased from approximately 1038 amperes to 2341 amperes when the wind speeds are 0.61 m/s and 12 m/s respectively. Most of the utilities rate the transmission based on the base wind speed of 0.61 m/s. Using the dynamic rating methodology, the rating of the conductor can be increased as this will accommodate the new wind generation during the high wind speed condition.

Base on the assumed values, the heat loss by conduction based on the wind speed and angle of incidence is calculated and the total ampacity of the conductor is determined using the formulae explained in the previous section.

An example of how dynamic line ratings might work on the system are calculated below.

> Wind Generation starts at about 3.5 m/s
> Max Wind Generation from 12 m/s to 25 m/s
> With Max generation at 12 m/s, assume nearby lines have 33% or 4 m/s wind
> Wind angle to line is 15 degrees (75 degrees to normal) then wind correction factor is 0.53
> Effective wind cooling speed m/s x 0.53 = 2.12 m/s
> Convention cooling increases 187% over 0.61 m/s in conductor tables
> Convection cooling is > 85% of total cooling so conductor dynamic rating will increase to 170% of table rating

This example shows how consideration of the wind can substantially increase the conductor rating of the lines. Dynamic line rating of the 230-kV lines at Pickert for 500 MW or the 115-kV lines at Mission for 250 MW could allow the existing lines to carry all of the power during a contingency.

3. Re-conductor of Transmission lines:

The technical studies and analysis for the Dakotas Wind Transmission Study found only a few overloaded transmission lines during contingency conditions and the level of overload indicated that dynamic rating was a better solution than rebuilding or re-conductoring transmission lines. Some of the options to re-conductor a transmission line are discussed below.

The thermal rating of existing power line can be often increased though a process of re-conductor, particularly with high temperature low sag conductors such as ACSS and other composite conductors. Re-conductor usually results in an increase in the rating of a line up to 50% without any modifications for structural reinforcements of the existing towers. Using these types of conductors, increase in the current carrying capacity of the transmission line for the same diameter does not increase the sag in the line with the increase in the current (temperature) flowing through it.

Other proven method for increasing the transmission line capacity is to re-tension the conductor. This can increase the clearances of the critical spans and therefore increase the line rating. Changing the type of conductor to ACSS (Aluminum Conductor Steel Supported) can increase the rating up to 25% while maintaining the same mechanical load in the towers. Also, using a trapezoidal type of conductor limits the conductor diameter and therefore limit the ice/wind loads on the existing towers while increasing the cross sectional area of the aluminum.

For re-conductoring, several new conductors can be considered for this purpose. Some commonly used are:

3.1 ACSS (Aluminum Conductor Steel Supported)

ACSS uses a fully annealed aluminum conductor around a steel core. The steel core provides the entire conductor support. The aluminum strands are “dead soft”, thus the conductor can be operated in excess of 200^0C without loss of strength. The maximum operating temperature of the conductor is limited by the coating used on the steel core (conventional galvanized coating can sustain 245^oC). Since the fully annealed aluminum cannot support significant stress, the conductor has a thermal expansion similar to that of steel. Tension in the aluminum strands is normally low. This helps to improve the conductor's self-damping characteristics and helps to reduce the need for dampers.

3.2 ACSS/TW (Aluminum Conductor Steel Supported / Trapezoidal Wire)

For ACSS/TW, the aluminum strands are trapezoidal in shape. The wedge shaped aluminum strands enable a more compact alignment of the aluminum wires. Conductor designs that maintain the same circular mil cross sectional area of aluminum as a conventional round conductor results in a TW conductor that is 10 to 15 percent smaller in overall diameter. Conductor designs that maintain the same overall diameter as a conventional round conductor result in a TW conductor that has 20 to 25 percent more aluminum cross-sectional area packed.

3.3 ACCR (Aluminum Conductor Composite Reinforced)

The Aluminum Conductor Composite Reinforced (ACCR) is a new type of bare overhead conductor containing a multi-strand core of heat-resistant aluminum composite wires, retains its strength at high temperatures and is not adversely affected by the environmental conditions, such as moisture and UV exposure. It's lightweight and reduced thermal expansion properties allow the conductors to be installed on existing towers and requires no additional changes.

The Composite Conductor is a non-homogeneous conductor consisting of high-temperature material strands (like aluminum-zirconium) covering a stranded core of fiber-reinforced composite wires. Both the composite core and the outer strands contribute to the overall conductor strength.

The composite core contains metal composite wires with diameters ranging from 0.073" (1.9 mm) to 0.114" (2.9 mm). The core wires have the strength and stiffness of steel, but with much lower weight and higher conductivity. Each core wire contains many thousand, ultra-high-strength, micrometer-sized fibers. The fibers are continuous, oriented in the direction of the wire, and fully embedded within high-purity aluminum. Visually, the composite wires appear as traditional aluminum wires, but exhibit mechanical and physical properties far superior to those of aluminum and steel. For example, the composite wire provides nearly 8 times the strength of aluminum and about 3 times the stiffness. It weighs less than half of an equivalent segment of steel, with greater conductivity and less than half the thermal expansion of steel. The outer strands are composed of a temperature-resistant material (like aluminum-zirconium alloy), which permits operation at high temperatures (210ºC continuous, 240ºC emergency). The Al-Zr alloy is a hard aluminum alloy with properties and hardness similar to those of standard 1350-H19 aluminum but a microstructure designed to maintain strength after operating at high temperatures; that is, it resists annealing. In contrast, 1350-H19 wires rapidly anneal and lose strength with excursions above 120-150ºC. The temperature-resistant Al-Zr alloy wire has equivalent tensile strengths and stress-strain behavior to standard 1350-H19 aluminum wires.

3.4 AAAC (All Aluminum Alloy Conductors)

AAAC is a high strength aluminum alloy, concentric-lay-stranded conductor and is similar in current carrying capacity as the equivalent size of ACSR. AAAC is similar in construction and appearance to ACSR.

Aluminum Alloy Conductors have a number of advantages over the ACSR

- Lower power losses than for equivalent single aluminum layer ACSR conductors (the inductive effect of the steel core in ACSR is eliminated).
- Simpler fittings than those required for ACSR
- Excellent corrosion resistance in environments conducive to galvanic corrosion in ACSR.
- Strength and sags are approximately same as for equivalent 6/1 and 26/7 ACSR conductors.

- Outside diameters are same as for the standard ACSR conductors permitting interchangeability of fittings.
- Greater resistance to the abrasion than that for 1350 wires in all aluminum or ACSR conductors.

3.5 Conductors Comparison

Table 1 below compares three of the conductors. The

Table 1: Comparison of properties for different Transmission Conductors (DRAKE SIZE)[1]

	ACSR	ACSS/TW	ACCR
Aluminum Area:	795 kcmil	795 kcmil	1020 kcmil
Size	Same	Same	Same
Weight	Same	Slightly higher	Same
Rated Ampacity (amperes):	905	1615	1902
Max Operating temp:	75°C	200°C	200°C
High Temp Sag:	High	Low	Very Low
Inductive Heating:	Standard	Low	Very Low
Line Loss:	Standard	Low	Less
Al Conductivity (%IACS):	52%	68%	63%
Tensile Strength	31,000 lbs	15,600lbs	41,000 lbs

[1] The characteristics of the Transmission line conductors represented in the table are just for comparison purpose. The details of each characteristic should change with the manufacturer and the different materials used for the conductors.

4. TRANSMISSION ENHANCEMENT BY SERIES CAPACITORS

Reactive compensation in power transmission systems has been a common practice in the power industry. The surge impedance loading (SIL) of a power transmission line is often used to indicate the nominal capacity of the line, especially for longer lines. At loadings greater than the SIL, it is necessary to supply Vars to the line in order to hold the voltage within normal limits. The SIL of a line can be increased by using series capacitor compensation, which results in a change in the inductive reactance of the line thereby increasing the steady state power transfer capability of the line. Figure 4.1 below shows how adding series compensation reduces the reactive power absorbed by the transmission line under heavy loading conditions.

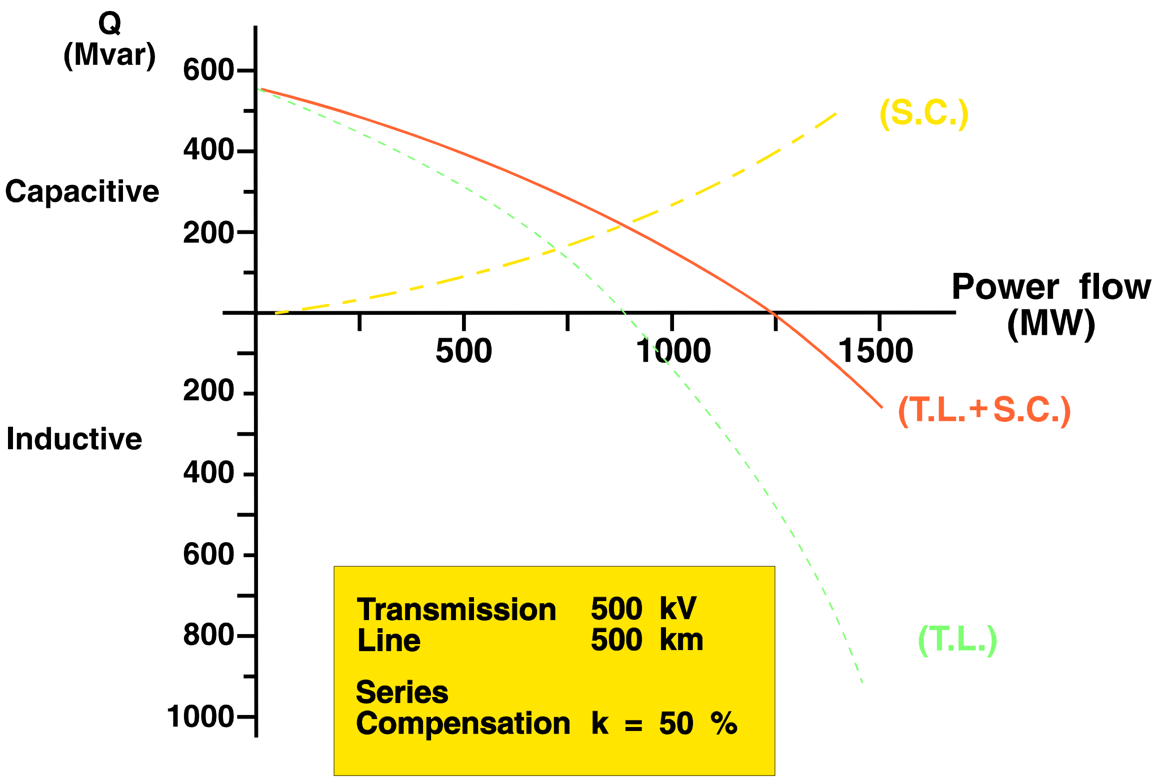

Figure 4.1 Transmission Line Reactive Power Losses with Series Capacitors

Series compensation also increases the voltage profile across the transmission systems under various loading conditions and also provides better control for load sharing and optimizing the losses in the transmission system.

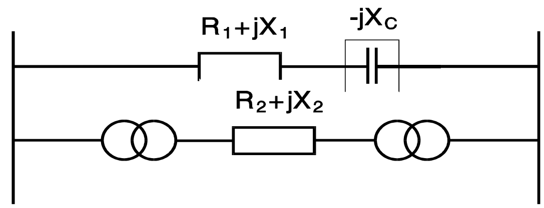

Figure 4.2 Example of Series Capacitors

Loss optimization as per the setup in the Figure above can be calculated using the formula:

$$(X_1-X_C) / X_2 = R_1 / R_2$$

Series compensation can have a significant effect on the stability of the system and its ability to survive major disturbances. The transient stability of the system is improved by series compensation due to the reduction in the overall series reactance and provides greater power transfer capability for a given angular difference between the nodes in the network. The power transferred is inversely proportional to the line reactance and 50% compensation reduces the reactance of the line by one-half, which provides twice the power transfer capability for a given angular difference. This is particularly true for the systems with long transmission lines, with great distances between the generation and loads. The figure below indicates the flows and voltages on two transmission lines with series compensation.

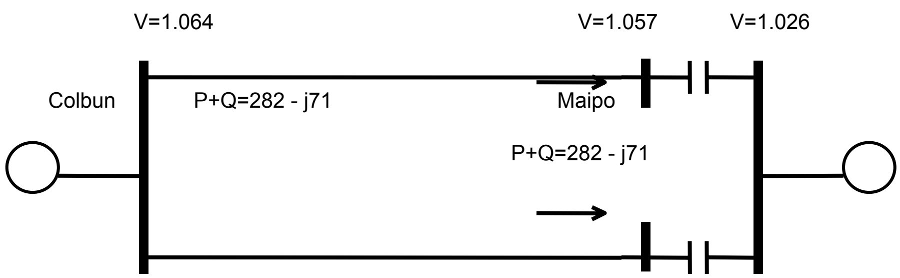

Figure 4.3 Voltage Profile with Series Capacitors for Normal System

Loosing one of the lines in this scenario with additional series compensation at the receiving end results in a good voltage profile across the transmission network as indicated in the figure below.

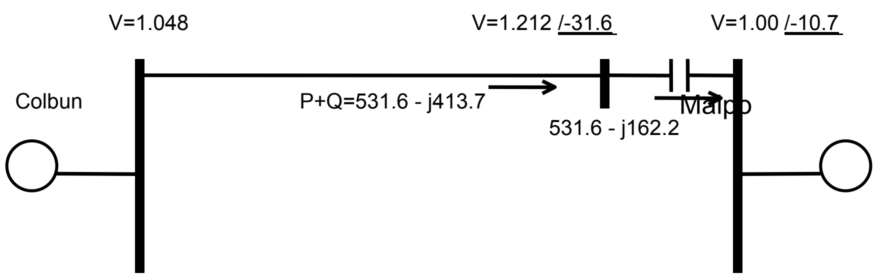

Figure 4.4 Voltage Profile with Series Capacitors for Outage Condition

The speed of the units in the nearby location can be plotted to compare the effect of the new compensation to the scenario without any compensation. Clearly, the figure below indicates the system to restore stability following the loss of a line.

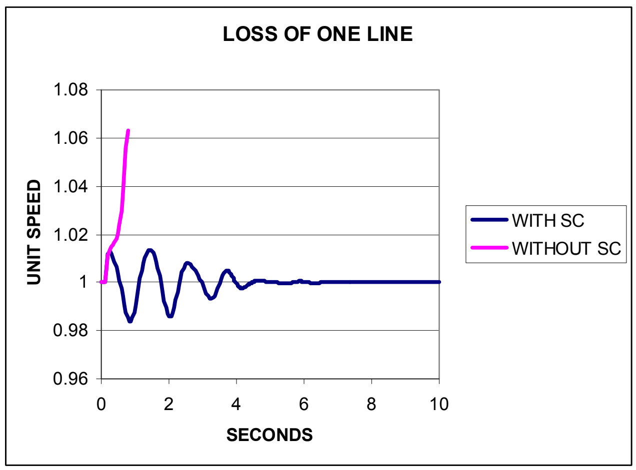

Figure 4.5 Stability of the Figure 4.3 System with and without Series Capacitors

The results from the regional stability analysis of the MAPP system discussed in the Task 4 report clearly indicate the stability improvements when the simulations were performed with 35% and 50% series compensation on some of the lines. The addition of series capacitors helped to both keep the power system in synchronism following a critical disturbance and reduce the voltage dip on the system. The results from the Task 4 study can be summarized as follows:

IMPACT OF ADDING CONVENTIONAL SERIES CAPACITORS
35% Series Compensation Increased transfers 100-250 MW for 7 Scenarios (About $4.5 M per installation):

- **Antelope Valley-Huron**
- **Leland Olds-Groton**
- **Leland Olds-Ft. Thompson**

50% Series Compensation Increased transfers 200-250 MW for 2 Scenarios (About $5 M per installation):

- **Antelope Valley-Huron**
- **Leland Olds-Groton**
- **Leland Olds-Ft. Thompson**

Series capacitors can be a very cost effective way to increase transmission capacity. There is one adverse impact that has been identified with series capacitors and that is the phenomena of subsynchronous resonance (SSR). Figure 4.6 below, the example of the generator shafts shows their characteristic resonance frequencies. If the series capacitor and the transmission system inductive reactance have a resonance that is the complement of the shaft resonance, oscillations below 60 Hz (therefore referred to as subsynchronous) can be amplified between the electrical system and the generator shaft. At one station in the early 1970's this was known to have damaged the shaft.

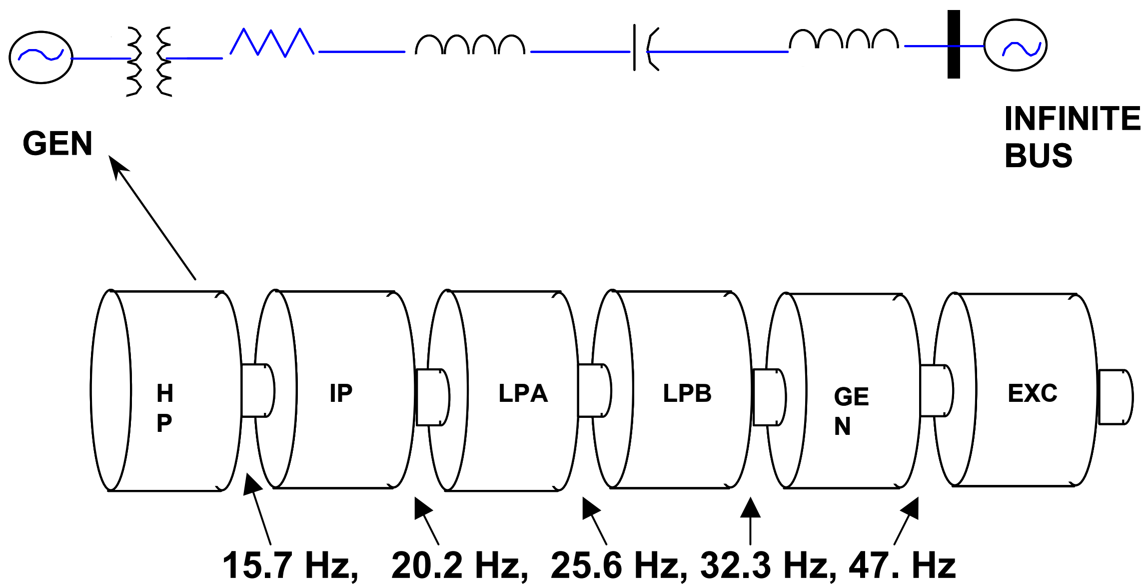

Figure 4.6 Subsynchronous Resonance of Series Capacitors and Generators

Some general rules about when SSR can be a problem are:

- The generators are large thermal steam generator units
- The series compensation is generally over 50%
- The generation can be isolated on the lines with series capacitors

In recent years, controllable series capacitors using thyristor valves have been designed. With the thyristor controlled series capacitors, SSR problems can be eliminated in those systems that would have a potential for SSR.

Thyristor controlled series compensators (TCSCs) are an extension of conventional series capacitors through adding a thyristor-controlled reactor. Placing a controlled reactor in parallel with a series capacitor enables a continuous and rapidly variable series compensation system. The main benefits of TCSCs are increased energy transfer, damping of power oscillations, damping of sub synchronous resonances found with conventional series capacitors and generators, and control of line power flow.

The addition of the thyristor valve does add significantly to the costs of a series capacitor installation. In most instances, only part of the total series capacitor needs to be controllable. Figure 4.7 shows how the total series compensation is split between conventional series capacitors and thyristor controlled series capacitors.

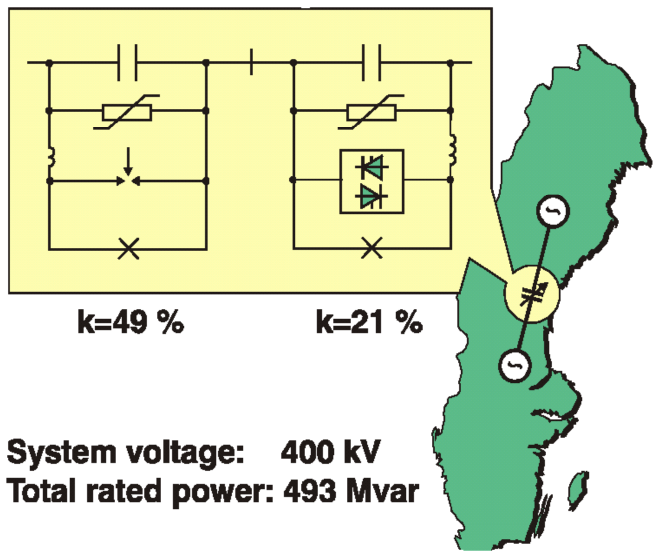

Figure 4.7 Example of Thyristor Controlled Series Capacitors

Thyristor controlled series capacitors should be considered if SSR is a problem or if system damping is required to reduce oscillations.

5. TRANSMISSION ENHANCEMENT BY SVCs AND STATCOMs

The use of Static Var Compensators (SVC's) or STATCOM's also provides the similar benefits to the series compensation. They provide reactive power support and can increase stability was well as help support the system voltage. An SVC can be used to improve transmission line economics by resolving dynamic voltage problems thereby increasing power transfers. The accuracy, availability and fast response enable SVC's to provide high performance steady state and transient voltage control compared with classical shunt capacitor compensation. SVC's are also used to damp power swings, improve transient stability, and reduce system losses by optimized reactive power control.

STATCOMs are power electronics based on voltage source converters. Compared with conventional SVC's (see above) they don't require large inductive and capacitive components to provide inductive or capacitive reactive power to high voltage transmission systems. This results in smaller land requirements. An additional advantage is the higher reactive output at low system voltages where a STATCOM can be considered as a current source independent from the system voltage. In general, for transmission applications there is little difference between the performance of an SVC or a STATCOM. The most economical solution should generally drive the technology used. Below are SVC and STATCOM applications.

a. DYNAMIC VOLTAGE SUPPORT
b. INCREASE POWER TRANSFERS
c. INCREASE TRANSIENT STABILITY
d. DAMP POWER OSCILLATIONS
e. BALANCE PHASE VOLTAGES
f. FLICKER AND VOLTAGE FLUCTUATIONS CONTROL
g. POWER FACTOR CORRECTION

In Task 4 the main requirement for the SVCs were for dynamic voltage support that resulted in increased wind power transfers. Simulations indicated some cases had low voltage dip problems in Groton area and in the northern Minnesota area. As a solution SVCs were modeled as described below:

1. **For the Garrison Site: three 200 MVAr SVCs in northern Minnesota eliminated the low voltages**
2. **For the Ellendale Site: one 200 MVAr SVC at Groton eliminated the low voltages**
3. **200 MVAr SVC about $11M**
4. **200 MVAr STATCOM generally 30% higher**

The SVCs and STATCOMs can be one solution to eliminating dynamic low voltage problems that limit power transfers from the wind sites.

6. ADDITION OF PHASE SHIFTING TRANSFORMERS

Phase shifting transformers can control the power through the transformer and this allows it to reduce loop flow thus increasing power transfers. Examples of this application are the phase shifting transformer at Boundary Dam in Saskatchewan that controls power on the Tioga line to North Dakota and the phase shifting transformer at Whiteshell that controls power between Ontario and Manitoba.

Phase shifting transformers add impedance to the system and in general reduce the system stability, although in the Northern MAPP system they may be useful in redirecting flows away from critical interfaces (e.g., the Manitoba Hydro Export –MHEX- Interface), and thus can be helpful in increasing transfer capability.

Main benefits of phase-shifting transformers are the protection of lines and transformers from thermal overload and sometimes an improvement of transmission system stability. They allow controlling the power flow between different networks, for parallel long distance overhead-lines or for parallel cables. Varying the voltage angle across the phase shifting transformer can control both the magnitude and the direction of the power flow. The series voltage can be varied by the tap changer in steps determined by the taps on the regulating winding. A phase-shifting transformer is very often the most economic approach to power flow management.

There were two sites with that resulted in overloaded lines. The first was the Pickert site with loss of one of the two 230-kV lines under summer rating conditions overloading the remaining line. The second was the Mission site for 250 MW on the 115-kV system and loss of one line. In both cases, there was not spare or unused capacity available in a parallel tie that could benefit from the use of a phase shifting transformer to reroute power.

A phase shifter might improve stability by shifting power going south and east to the north through Manitoba Hydro, but the transfers from Manitoba Hydro into Minnesota were already stability limited and therefore the phase shifting transformer in this case can only improve one stability limit by impacting another stability limit. In this system there was limited opportunity to shift power between NDEX and Manitoba Hydro export to increase stability.

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